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**NUCLEAR AEROSPACE RESEARCH FACILITY**

**DETERMINATION OF MEAN OPERATING  
LIFE AND SHELF LIFE FOR THE RADIATION  
SURVEY METER AND PERSONAL  
RADIATION DOSIMETER BATTERY PACKS**

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Prepared for  
**MANNED SPACECRAFT CENTER  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
HOUSTON, TEXAS**

**Contract No. NAS9-11515**

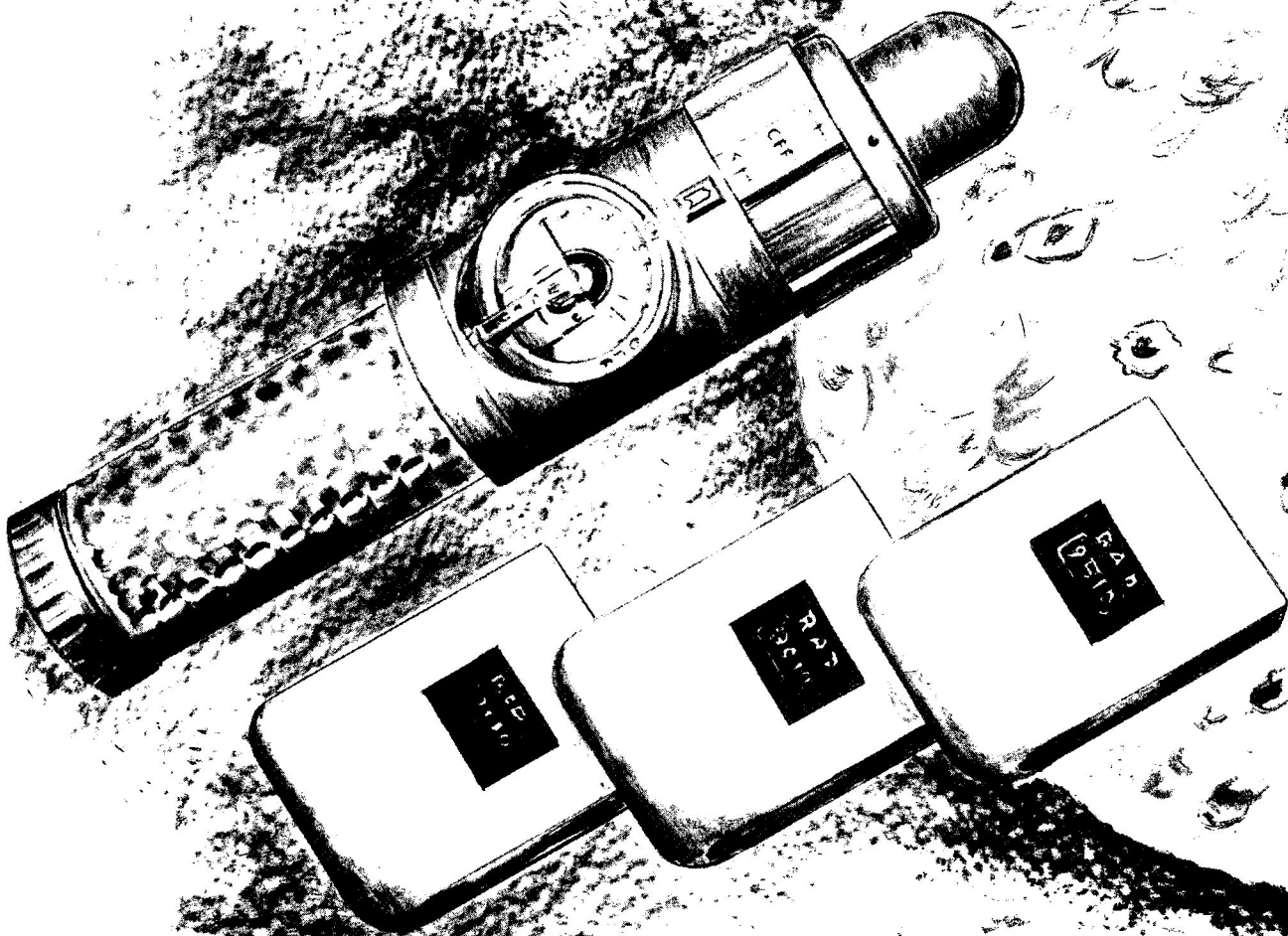
**GENERAL DYNAMICS**

***Convair Aerospace Division***

***Fort Worth Operation***

CR-115189

**DETERMINATION OF MEAN OPERATING  
LIFE AND SHELF LIFE FOR THE RADIATION  
SURVEY METER AND PERSONAL  
RADIATION DOSIMETER BATTERY PACKS**



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## FOREWORD

This document represents the final report, with the exception of the shelf-life test, for NASA Contract NAS9-11515. The primary purpose of these tests was to determine if the operating life of the various types of mercury cell battery packs that can presently be used in the Personal Radiation Dosimeter (PRD) and the Radiation Survey Meter (RSM) is long enough to power these instruments on the proposed Skylab missions.

## I. INTRODUCTION AND SUMMARY

The Convair Aerospace Division has completed tests to determine the mean operating life of four types of battery packs for use in two types of Apollo radiation measuring instruments, the Personal Radiation Dosimeter (PRD) and the Radiation Survey Meter (RSM).

This battery pack operating life test was conducted to determine if the battery packs presently being used in the PRD and RSM units on the short Apollo missions (10 days) would operate properly for the much longer (56 days) Skylab missions.

The results of these tests have proven conclusively that the presently used PRD battery pack containing eight BA-1006/U mercury cells will not operate properly for the 56-day Skylab mission, but these tests have also shown that a battery pack containing eight PX-625 mercury cells will operate throughout the Skylab mission.

The results of these tests have also shown that the two RSM battery packs that now contain eight RM-625R mercury cells each will not operate the RSM properly for a 56-day Skylab mission and neither will any of the other three types of mercury cells tested. This means that a new battery pack containing more current capacity will have to be designed for the RSM for the Skylab missions.

The PRD is worn by each astronaut to measure time-integrated dose. The instrument weighs one-half pound, and its dimensions are 0.8 in. by 2.2 in. by 3.3 in. It has a five-digit readout in 10-millirad-tissue increments and operates on one 10.8 V mercury battery pack. The RSM monitors the rate of radiation and is mounted within the spacecraft, or can be hand-carried. It weighs one and three-quarter pounds, is 2.25 in. in diameter, and 9.0 in. long. The RSM operates on two 10.8 V mercury battery packs. Both instruments utilize tissue-equivalent ionization chambers with an energy response of  $\pm 10\%$  from 0.5 MeV electrons to 150 MeV protons.

The PRD and RSM were designed for use on the Apollo missions with emphasis on reliability, minimum size and weight. Consequently, the useful battery life is long enough for an Apollo mission but not long enough for a Skylab Mission. The advent of Skylab prompted this study to determine long-term operational battery-life requirements for the PRD and RSM.

The four types of batteries tested were as follows:

1. Mallory RM-625R - These are used in the RSM units.
2. Mallory BA-1006/U - These are used in the PRD units.
3. Mallory RM-625 - These cells have a 1.4 V output, whereas the other three types have a 1.35 V.
4. Mallory PX-625 - These are new, higher reliability batteries.



Five different operational load conditions were used for the tests, including current pulses to simulate the operation of the PRD readout counter.

The results of these tests, shown in Table 1-1, are described briefly as follows.

- . BA-1006/U's have a MTBF of 73 days at 100 $\mu$  amps drain (PRD); 41 days at 200 $\mu$  amps drain (RSM); and 68 days up to an equivalent 20 mr/hr field on the PRD. Shelf-life tests have not been completed, but there are no failures at 200 days on 10 battery packs.
- . RM-625's have a MTBF of 63 days at 100 $\mu$  amps and 36 days at 200 $\mu$  amps.
- . RM-625R's have a MTBF of 43 days at 100 $\mu$  amps and 28 days at 200 $\mu$  amps.
- . PX-625's have a MTBF of 110 days at 100 $\mu$ amps and 57 days at 200 $\mu$  amps. These cells have the longest operating life of the four types in the test.

The radiation instrument battery requirements for Skylab can be obtained from the data of these tests and other requirements such as percent confidence, operational procedures, and mission time.

Table 1-1

## SUMMARY OF BATTERY FAILURE DATA

Test No.	Mercury Cell Type	Current in Microamps	No. Batteries per Test	No. of Failures	Elapsed Days		MTBF Days	Std. Dev., %
					First Failure	Last Failure		
1	BA-1006/U	0 (shelf life)	10	0	No failures	200 days		
2	PX-625	100	15	15	78	127	110.2	15.0
	BA-1006/U	100	15	15	56	83	73.7	13.7
	RM-625	100	15	15	48	82	62.4	17.8
	RM-625R	100	15	15	19	70	43.4	48.7
3	PX-625	200	15	15	44	64	56.8	11.1
	BA-1006/U	200	15	15	35	45	41.5	9.6
	RM-625	200	15	15	30	44	36.0	9.5
	RM-625R	200	15	15	12	42	27.9	40.9
4	BA-1006/U	100+(20 mr/hr)	20	20	51	79	67.5	13.8
5	BA-1006/U	100+(2 mr/hr)	20	20	57	76	67.1	7.6

## II. TEST CONDITIONS AND PROCEDURES

Five types of tests were conducted on four types of battery packs. The PRD draws approximately 100  $\mu$  amps of current when in a quiescent state, and more current when it is operating in a radiation field. The RSM draws approximately 200  $\mu$  amps at 50% full-scale reading on the meter. The tests included simulated operation of the PRD readout events counter at two different rates.

Battery packs were made up using eight mercury cells per pack. Details of the five tests performed are summarized in Table 1-1 and described below.

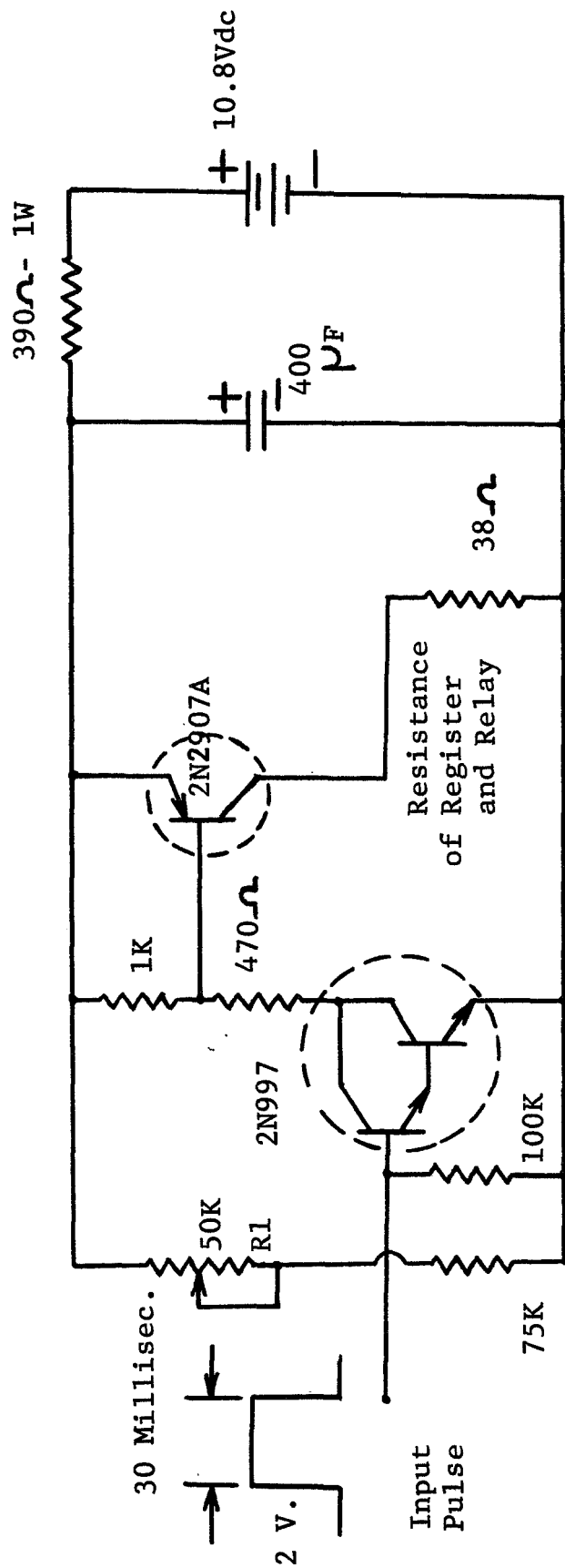
Battery packs used in tests 1, 4, and 5 consisted of BA-1006/U cells. Battery packs in tests 2 and 3 used BA-1006/U, RM-625, RM-625R, and PX-625 cells. Test 1 battery voltages are read weekly. All other test battery voltages were read once each day. A battery pack was considered to have failed when its terminal voltage decreased to 9.0 V. This value is the minimum for satisfactory PRD and RSM operation.

In test 1 (shelf-life storage test) ten battery packs are being used with no spares. This is a shelf-life storage test with no current drawn from the batteries. This test will be continued for ten months, or until all battery packs fail. However, the total length of the test shall not exceed 10 months.

In test 2 (PRD battery test) each battery pack had a resistive load which placed a  $100\ \mu$  amps current drain on the battery pack. Each battery pack in test 3 (RSM battery pack test) had a resistive load sufficient to place a  $200\ \mu$  amps current drain on the battery pack. Fifteen battery packs of each battery part number were used in both tests, and both tests were continued until all battery packs failed.

In test 4 (PRD unit in a 20 mr/hr field) ten battery packs were used initially with ten battery packs used as replacements for failed units. Tests were continued until all 20 battery packs failed. Ten test circuits were designed and fabricated equivalent to the PRD electronics with a 38-ohm resistive load used instead of the register and relay coils. These circuits are shown in Figure 2-1. A resistance sufficient to load the battery pack to the required test steady-state current requirements was added across the battery packs. A pulse train was divided by flip-flop circuits so that the output pulse obtained was at a rate of 2 pulses per hour, which is the equivalent of 20 mrad/hr. This pulse was used to drive the PRD circuits for test 4. This circuit is shown in Figure 2-1, and a block diagram of the instrumentation for this test is shown in Figure 2-2.

In test 5 (PRD unit in a 2 mr/hr field) ten battery packs were used initially and ten battery packs used as replacements for failed units. These tests were continued until all 20



\* Adjust R1 for total current from battery of  $100\mu\text{A}$  with no input pulses.

Typical of 10 circuits for Test #4 and 10 circuits for Test #5

Figure 2-1 Test Circuit for Battery Life Tests #4 and #5

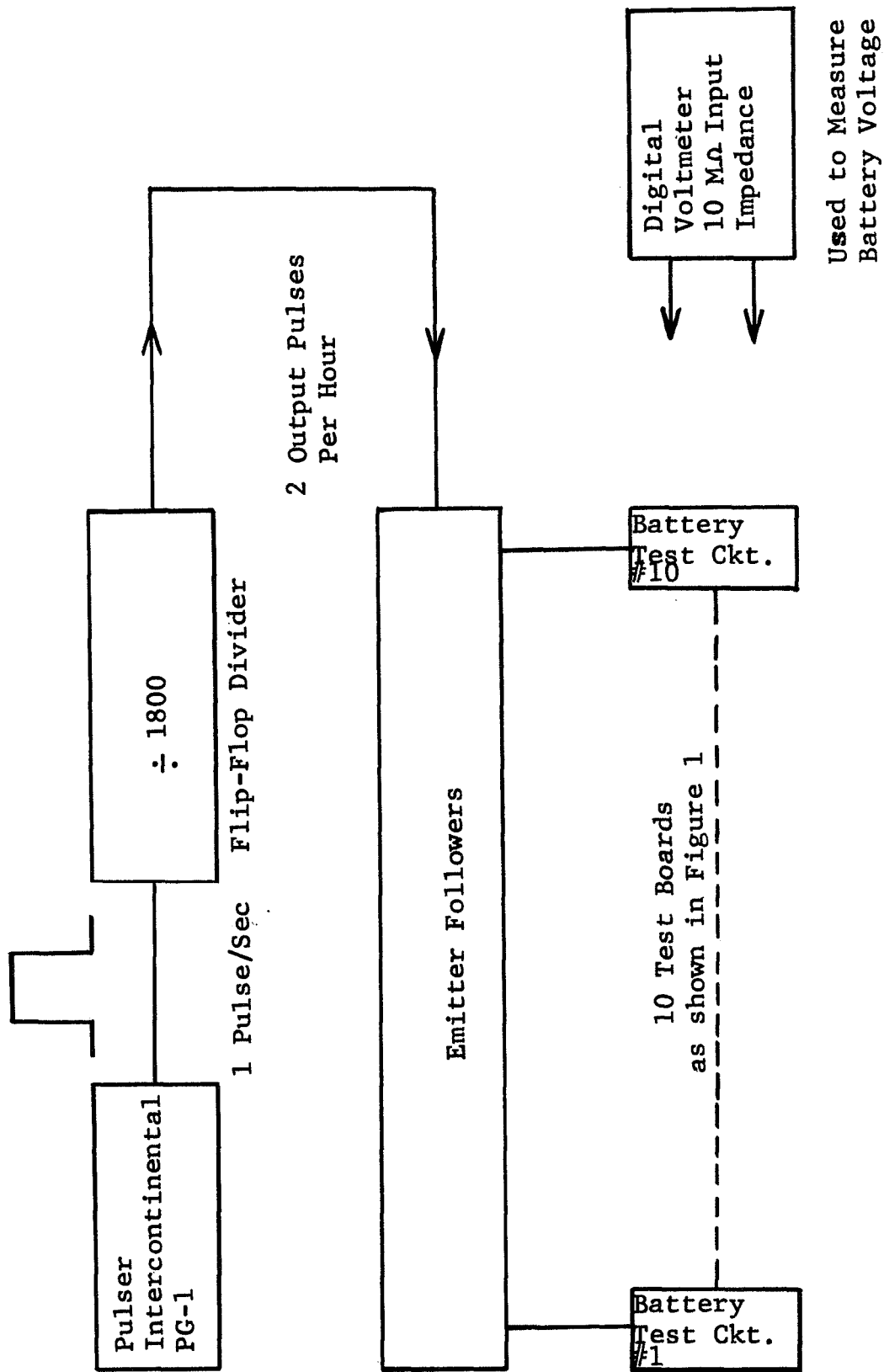


FIGURE 2-2 MERCURY CELL LIFE TEST AT 100 $\mu$ A AND 20 mr/hr FIELD,  
TEST INSTRUMENTATION BLOCK DIAGRAM

battery packs failed. Ten test circuits identical to the ones in test 4, described above and shown in Figure 2-1, were used. They were the equivalent of a PRD electronics circuit with a 38-ohm resistive load used to replace the relay and register coil. A pulser was switched manually to each of the ten test circuits for test 5, and each simulated PRD circuit drew 100  $\mu$  amps of current from its mercury cell package. It was pulsed manually at a rate equivalent to a 2 mrad/hr field or one pulse each five hours. A block diagram of the test instrumentation is shown in Figure 2-3, and a photograph of the instrumentation is shown in Figure 2-4.

Tests 4 and 5 were run concurrently using ten test circuits for test 4 and ten test circuits for test 5, for a total of 20 test circuits. When the first ten battery packs had failed, ten more battery packs were installed and operated until failure.

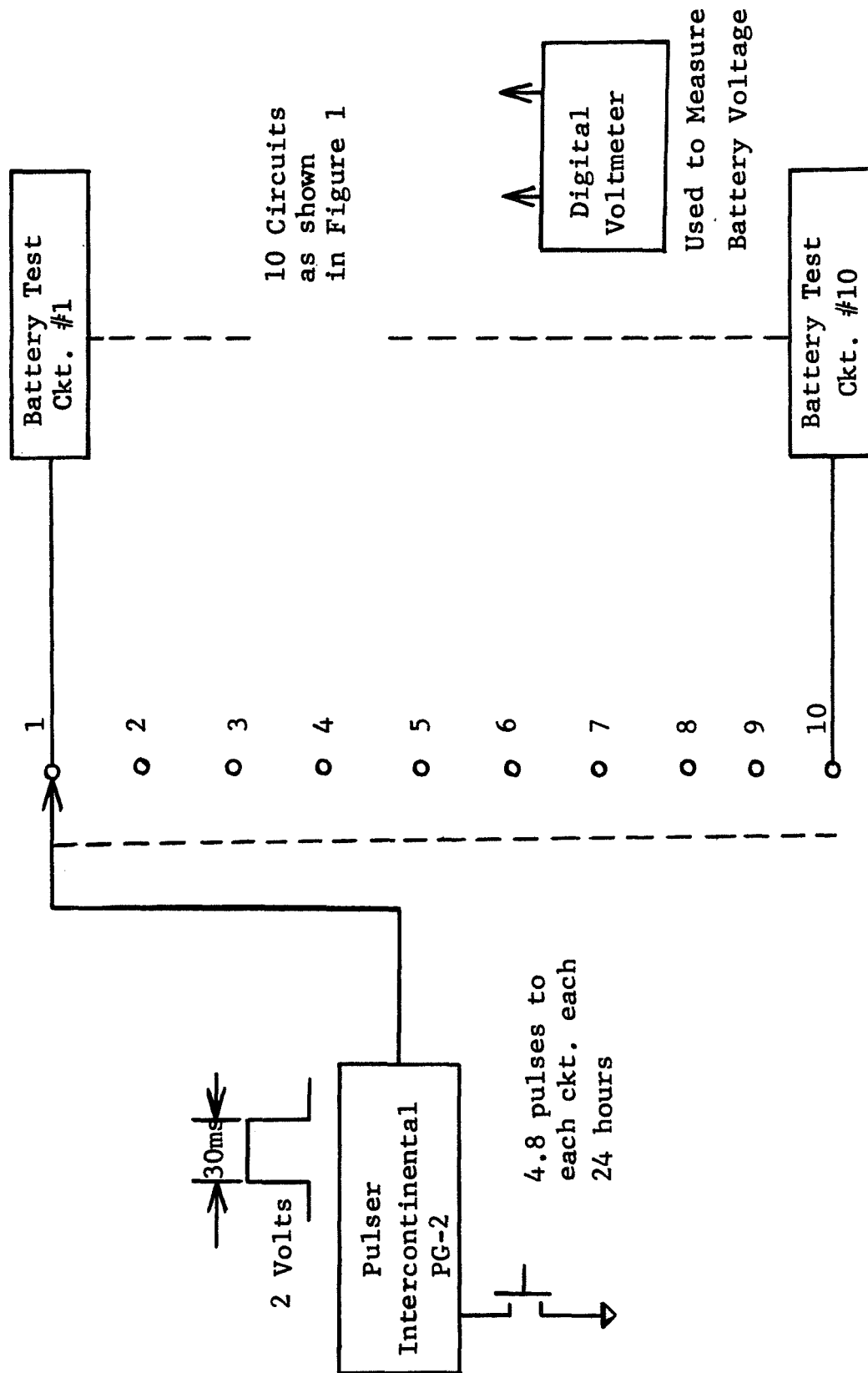


FIGURE 2-3 MERCURY CELL LIFE TEST AT 100 $\mu$ A AND 2 mr/hr FIELD  
TEST INSTRUMENTATION BLOCK DIAGRAM



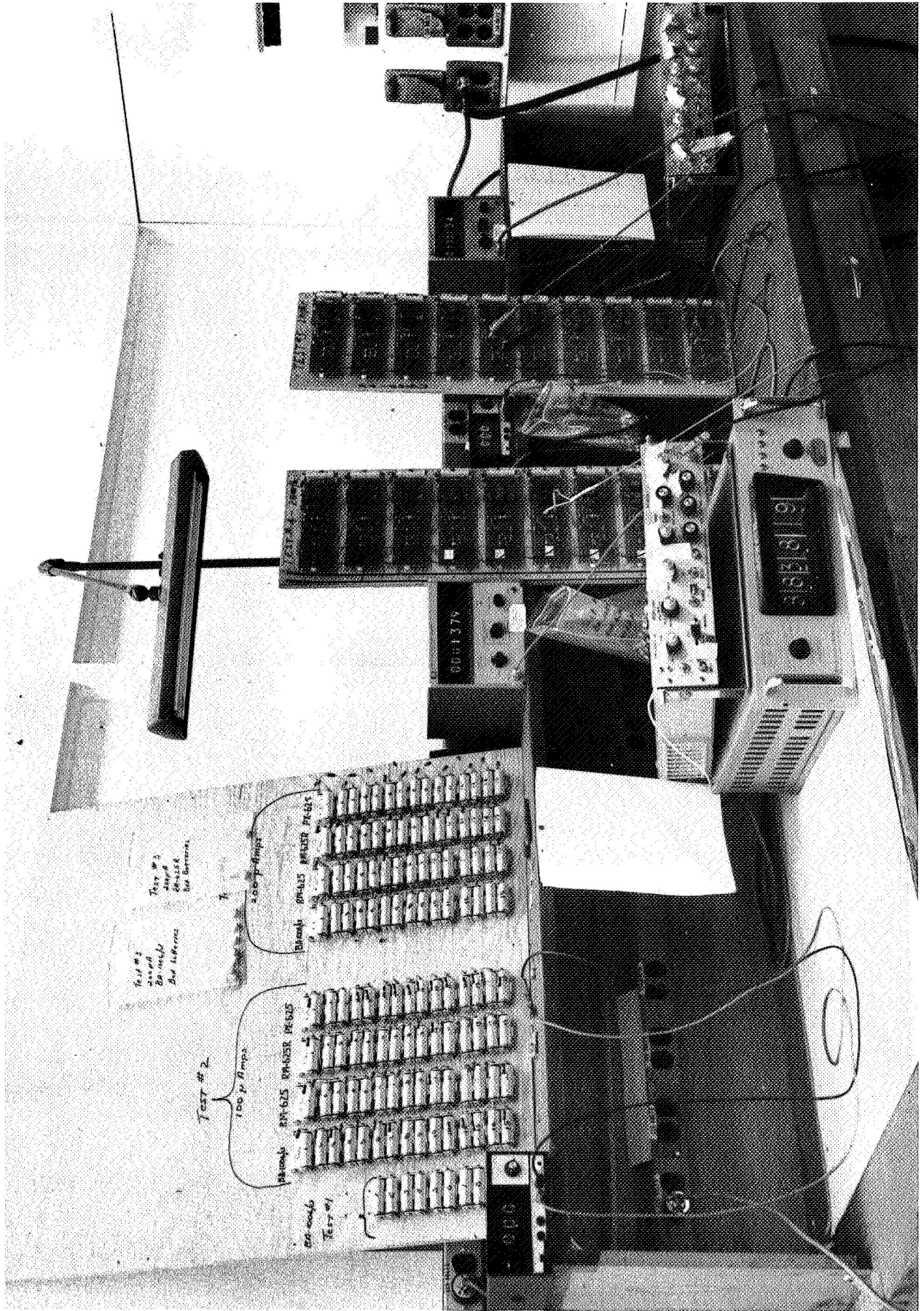


Figure 2-4 Instrumentation for Battery Life Test

### III. ANALYTICAL PROCEDURES

An important step in a statistical analysis of a given set of observations is the mathematical formulation of the type of distribution of the population. The distribution may sometimes be derived from the available knowledge of the physics of the material, but as a rule a distribution type must be assumed or chosen from an empirical distribution based on observational data.

The observed data (i.e., days to failure) for each set of N battery packs were plotted on various probability papers (normal, lognormal, and exponential). Probability paper is used in the same manner as other special graph papers such as logarithmic paper. If we plot the observed values on the paper, we can then decide whether it is reasonable to describe their relationship by a function of the type represented by a straight line on the paper.

On the basis of all the data plots, the lognormal was selected as the underlying failure distribution which "best" describes the battery pack data. The exponential assumption was used for preliminary reporting of the results prior to an analysis of the combined data, therefore, there will be slight deviations in this report from those reported in preliminary progress reports.

The transformation of the observed battery pack data,  $X_i$ , to  $\log X_i$  results in new data,  $Z_i$ , which can be reasonably characterized by the Normal Distribution. Thus, the results of Normal Distribution theory are used to analyze the transformed data.

The average or MTBF (mean-time-between-failure) is the geometric average and is estimated by:

$$\hat{MTBF} = \text{Antilog}(\bar{Z}); \quad \bar{Z} = \frac{1}{N} \sum_{i=1}^N Z_i$$

The standard deviation,  $\sigma$ , is estimated by

$$\hat{\sigma} = \left\{ \sum_{i=1}^N \frac{(Z_i - \bar{Z})^2}{N - 1} \right\}^{\frac{1}{2}}$$

( $\hat{\sigma}$  - estimate)

The data tables 4-1 through 4-4 (see next section) contain the failure times, i.e.,  $X_i$  data, the  $\hat{MTBF}$ ,  $\bar{Z}$ ,  $\hat{\sigma}(\log)$ , and  $\hat{\sigma}$  in percent.

One sided tolerance intervals are used to estimate the reliability of a battery pack with a  $100(1-\alpha)\%$  confidence level. The results are presented as:

$$R(D) \geq P,$$

i.e., we are  $100(1-\alpha)\%$  confident that at least  $P\%$  of the battery packs considered will survive  $D$  days. The one-sided tolerance

intervals presented in the form of reliability are obtained from the following:

$$D = \text{Antilog}(\bar{Z} - k\alpha\hat{\sigma}) \quad (1)$$

where  $k^*$  is the tolerance factor dependent on  $\alpha$ ,  $N$ , and  $P$ ;

$\alpha$  is the confidence coefficient.

For an example, consider the data for BA-10006/U with a 100  $\mu$ A load (Test 2 ):

$$\bar{Z} = 1.8675$$

$$\hat{\text{MTBF}} = \text{Antilog}(1.8675) = 73.7 \text{ days}$$

$$\hat{\sigma}(\log) = 0.0558 \quad \hat{\sigma}(\%) = 13.7$$

For  $\alpha = 0.05$ ,  $N = 15$ ,  $P = 0.99$ ,  $k = 3.52$ . From (1),

$$D = \text{Antilog} \left[ 1.8675 - 3.52(0.0558) \right] = 46.9 \text{ days}.$$

Thus

$$R(46.9 \text{ days}) \geq 0.99$$

i.e., we can be 95% confident that at least 99% of the BA-1006/U battery packs operating at 100 $\mu$ A will survive 46.9 days. Putting this statement into reliability language, we can be 95% confident that the reliability over (0-46.9) is  $\geq 0.99$ . Reliability,  $R(D)$ , values have been calculated for  $P = 99\%$  and  $99.9\%$  and  $\alpha = 0.05$  for each battery pack and test sequence (shelf life excepted).

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\*Bowker, A. H., Lieberman, G. J., "Table of Tolerance Factors for Normal Distribution," Engineering Statistics, Prentice-Hall Inc., 1959.

#### IV. TEST RESULTS

All calculational results presented in the tables in this section were carried out as indicated in Section III.

##### 4.1 Test No. 1 - Shelf-Life Tests

There have been no failures in over 200 days on ten BA-1006/U battery packs. Failure results in ten months of shelf-life tests will be reported later. The results to date indicate that the batteries will have to be stored in vacuum-tight bags with a thin layer of non-conductive vacuum grease on them to prevent corrosion.

##### 4.2 Test No. 2 - 100 Microamperes, PRD Tests

The results of 15 battery packs each of BA-1006/U, RM-625R, RM-625, and PX-625 are tabulated in Table 4-1. The MTBF for the presently used BA-1006/U is 73.7 days while the new PX-625 shows a considerably longer life at 110.2 days.

##### 4.3 Test No. 3 - RSM Operating at 200 Microamperes

This test places the same load on each battery pack as the RSM unit does when the RSM meter indicates 50% of full scale. Fifteen battery packs of four different types of mercury cells were used for a total of 60 battery packs. The test results of 15 packs each of PX-625, BA-1006/U, RM-625 and RM-625R are tabulated in Table 4-2. The PX-625 has the best MTBF of 56.8

Table 4-1

## TEST 2 - 100 MICROAMPERES

Battery Type	Elapsed Days Until Battery Pack Failure			
	PX-625	BA-1006/U	RM-625	RM-625R
Battery Pack No.				
1	123	72	57	67
2	127	80	54	46
3	111	84	48	70
4	123	68	49	53
5	109	62	61	49
6	118	84	56	46
7	118	94	75	22
8	116	76	75	57
9	115	80	56	52
10	120	71	82	46
11	84	68	72	56
12	98	72	72	19
13	116	71	65	26
14	112	76	60	32
15	78	56	69	54
MTBF, days	110.2	73.7	62.6	43.4
$\bar{Z}$	2.0424	1.8675	1.7967	1.6378
$\hat{\sigma}(\log)$	0.0609	0.0558	0.0712	0.1722
$\hat{\sigma}(\%)$	15.0	13.7	17.8	48.7

Table 4-2

## TEST 3 - 200 MICROAMPERES

Battery Type	Elapsed Days until Battery Pack Failure			
	PX-625	BA-1006/U	RM-625	RM-625R
Battery Pack No.				
1	63	42	37	12
2	59	32	35	34
3	64	43	36	36
4	61	45	35	23
5	50	43	37	14
6	60	39	37	31
7	49	45	44	26
8	58	42	37	31
9	60	45	39	35
10	60	44	32	33
11	59	45	39	30
12	55	43	34	31
13	61	38	37	27
14	54	40	33	42
15	44	39	30	33
MTBF, days	56.8	41.5	36.0	27.9
$\bar{Z}$	1.7547	1.6182	1.5562	1.4451
$\hat{\sigma}(\log)$	0.0456	0.0399	0.0396	0.1490
$\hat{\sigma}(\%)$	11.1	9.6	9.5	40.9

days as compared to 27.9 days for the RM-625R presently used in the RSM.

4.4 Test No. 4 - 100  $\mu$ amps + 20 mr/hr,  
Test No. 5 - 100  $\mu$ amps + 2 mr/hr

Test Nos. 4 and 5 were performed to simulate a PRD operating in a 2 mr/hr and a 20 mr/hr radiation field. Twenty battery packs each were used in tests 4 and 5. Electronic circuits (see Fig. 2-1) were built to life-test these battery packs, and they drew exactly the same current as an actual PRD unit would in a 2 and 20 mr/hr field. The BA-1006/U mercury cells were used in the battery packs for these tests since they were the mercury cells used in the PRDs for all Apollo missions.

The test results from the 20 battery packs operated at 100  $\mu$ amps + 2 mr/hr and the 20 battery packs operated at 100  $\mu$ amps + 20 mr/hr gave almost identical results as is shown in Tables 4-3 and 4-4. The MTBF for both irradiation rates is approximately 67 days.

4.5 Reliability

Using the procedures described in Section III, the battery failure data may be analyzed for any desired combination of % confidence, % battery packs surviving, and minimum number of days surviving. We cannot presume to know the particular combination of prime interest to NASA, but results of the analysis of each battery pack type for all the specified stresses (i.e.,



TABLE 4-3

Test 4 BA-1006/U @ 100  $\mu$ A+20 mr/hr

Battery Pack No.	Elapsed Days Before Failure
1	68
2	71
3	79
4	70
5	69
6	78
7	70
8	79
9	66
10	53
11	63
12	70
13	77
14	64
15	72
16	77
17	67
18	60
19	57
20	50
MTBF, days	67.5
$\bar{z}$	1.8292
$\hat{\sigma}(\log)$	0.0560
$\hat{\sigma}(\%)$	13.8

TABLE 4-4

Test 5 BA-1006/U @ 100  $\mu$  A+2mr/hr

Battery Pack No.	Elapsed Days Before Failure
1	62
2	72
3	63
4	68
5	76
6	73
7	66
8	64
9	63
10	73
11	72
12	69
13	66
14	72
15	72
16	59
17	67
18	59
19	66
20	65
MTBF, days	67.1
$\bar{z}$	1.8272
$\hat{\sigma}(\log)$	0.0318
$\hat{\sigma}(\%)$	7.6

battery loads) are presented in Table 4-5 for a 95% confidence interval with 99% and 99.9% of the battery packs surviving. For example, we can be 95% confident that at least 99% of all RM-625 battery packs under a  $200\mu$  amp load will last at least 26.1 days.

Table 4-5

95% Confidence Interval for at Least P%  
of the Battery Packs Surviving D Days

Battery Pack	Stress Level	MTBF, days	D, days	
			P=99%	P=99.9%
PX-625	100 $\mu$ amps	110.2	67.3	57.8
	200 $\mu$ amps	56.8	39.3	35.0
BA-1006/U	100 $\mu$ amps	73.7	46.9	40.8
	200 $\mu$ amps	41.5	30.0	27.2
RM-625	100 $\mu$ amps	62.6	35.2	29.4
	200 $\mu$ amps	36.0	26.1	23.6
RM-625R	100 $\mu$ amps	43.4	10.8	7.0
	200 $\mu$ amps	27.9	8.3	5.7
BA-1006/U	100 $\mu$ amps + 20 mr/hr	67.5	44.1	38.7
BA-1006/U	100 $\mu$ amps + 2 mr/hr	67.1	52.8	49.0

## V. CONCLUSIONS AND RECOMMENDATIONS

The results of the battery life test 2 show that the PX-625 battery packs are the leading candidates for use in the PRDs in their present configuration for the Skylab missions. The MTBF using such a pack under the PRD load (i.e., 100  $\mu$  amps) is 110.2 days. As can be seen from Table 4-5, we can be 95% confident that at least 99% of all PX-625 battery packs under a 100  $\mu$  amp load will last at least 67.3 days. We have presented the data (Table 4-1) and the analytical method (Sec. III) by which NASA may calculate any other desired combination of % confidence, % battery packs surviving, and minimum number of days surviving and thereby decide whether or not this battery pack/PRD system is reliable enough to use "as is" on Skylab missions. It is our feeling that this system is reliable enough.

The results of battery life test 3 in which all four types of battery packs drew 200  $\mu$  amps of current to simulate the current drawn by the RSM are conclusive. The PX-625 battery pack had the longest MTBF (56.8 days) of the types tested. Since the RSMs would have to ready some time (possibly days) before launch, the MTBF would have to be considerably longer than 56.8 days. The results thus indicate that none of the four types of batteries tested would last long enough to operate the RSM for the Skylab mission. Listed below are several

methods that could be used to obtain the necessary operating life for the RSM.

1. Change battery packs after approximately 30 days using the PX-625 mercury cells and the present battery pack.
2. Modify the existing battery pack to contain twice as many PX-625 mercury cells thereby doubling the battery operating life.
3. Install reed switches in the Hi-Z module in the RSM so the unit can be turned off when not in use.
4. Install a mechanical switch on the end of the handle so the RSM can be turned off when not in use.
5. Carry two RSMs, operating one for the first half of the mission and the other for the last half of the mission.
6. Modify the present battery pack so that a PX mercury cell with a slightly larger current capacity could be used to obtain the desired operating life before failure.
7. Use a different type of cell, such as a silver cell, to obtain larger current capacity and modify the present battery pack to contain this new battery.
8. Use rechargeable batteries and recharge from the ship's power.

The method used in order to obtain the longest operating life for the RSM will depend on factors such as time, physical limits, and budget. The best, long-range modification of the RSM would be to increase the battery life of the unit to the maximum extent possible so it could be used on later missions of longer duration as well as on the Skylab missions. The

battery life of the RSM could be extended to approximately 100 days by installing mercury cells or silver cells with 500 ma-h current capacity. The power on-off switch could be installed, and this would increase the battery life by a factor of ten if the unit were turned on 10% of the time.

An interesting result of the PRD battery test is the similar MTBF rates of the BA-1006/U battery packs when operated in radiation fields of 0, 2 and 20 mr/hr.

			<u>MTBF</u>
BA-1006/U	100 $\mu$ amps	20 mr/hr	67.5 days
BA-1006/U	100 $\mu$ amps	2 mr/hr	67.1 days
BA-1006/U	100 $\mu$ amps	0 mr/hr	73.7 days

These data show there is a very small difference of battery lifetime when the PRDs are operated in a radiation field of 0, 2, and 20 mr/hr.

Figure 5-1 is a plot of a typical PX-625 battery pack operated at 100 and 200  $\mu$  amps drain current. These data are included to show the variation in voltage during the first 15 days of battery pack operation. This early variation in voltage does affect the gain of the PRD during actual operation. The PRD reads approximately 5% low until the battery voltage approaches stabilization after three days of operation. This stabilization time can be stepped up to one day by placing the PRD in a 1 rad/hr field for one day.

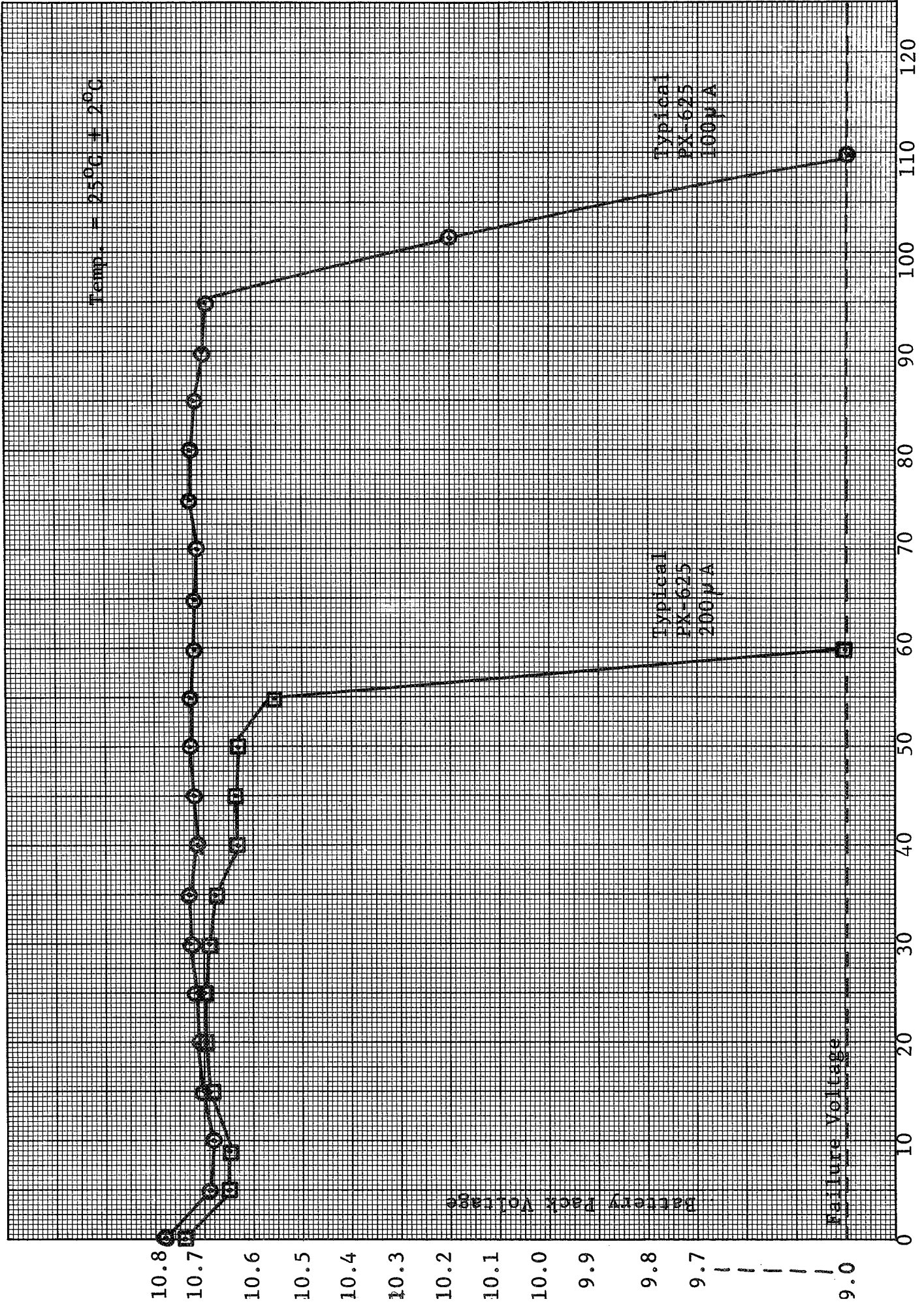


Figure 5-1 Battery Pack Voltage vs. Elapsed Days